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CARBON MONOXIDE LASER

Robert E. Center

Avco Everett Research Laboratory, Incorporated

Prepared for:

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CARBON MONOXIDE LASER
FINAL TECHNICAL REPORT
PHASE I

Contract No. N00014-72-C-0030
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AVCO EVERETT RESEARCH LABORATORY, INC.
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FOREWORD

ARPA Order No:	1807
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ABSTRACT

This report describes the development of a 20 liter cooled CO laser designed for pulsed operation with pressures up to 1 atmosphere. An electron beam sustained discharge is used for the gas excitation. Pulsed output energies up to 1 kilojoule have been observed and the results are compared with the theoretical predictions based on a kinetic model for the CO laser.

SUMMARY

The main objective of this program is the investigation of pulsed electrical CO lasers to determine their potential scaling to large scale, high power operation. The program is based on the application of the electron beam ionizer-sustainer concept to the vibrational excitation of CO with temperature controlled operation.

The following areas of investigation are included in the current contract:

1) Investigation of the electron beam current requirements and the E/p range for sustainer discharge excitation of CO and CO/N_2 mixtures.

2) Design and construction of the electron gun and laser cavity for operation at gas temperatures from $100^{\circ}K$ to $300^{\circ}K$.

3) Experimental investigation of the multiline/multimode operation over a range of gas temperature and pressure up to the equivalent of one atmosphere at room temperature.

4) The extension of the theoretical model to the directly excited CO laser including calculations of the transient gain and power.

Despite considerable delays in the fabrication of the variable temperature discharge electrodes, the above goals have been met with

the main results being the successful construction and testing of a cryogenically cooled device with an output pulse energy of up to 1 kilojoule. In addition, the following technical results were achieved during this initial program.

1) Measurement of the electron ion recombination rates in CO plasmas at pressures up to 1 atmosphere and average electron energies from .2 to .7 eV.

2) The design and construction of the broad area, 20 cm x 100 cm, electron beam and power supply with current densities up to 10 mamp/cm^2. Also, the design and construction of a 20 liter temperature controlled cavity together with the associated electronic control circuitry.

3) The extension of the theoretical model to the case of the uniformly excited CO laser including calculations of transient gain and power.

4) The overall integration of the cold flow system and the electrical excitation systems.

5) Measurements of total pulse energy as a function of pulse length and the temporal variation in the pulse shape in CO/N_2 mixtures under cold operating conditions.

Items 1, 2 and 3 have been described in an earlier report and the present report will be confined to description of the overall system test and application including preliminary measurements of the cold flow uniformity. A brief description is given of the development of a useful calorimeter for the measurement of the high peak power output pulses and the experimental energy measurements are compared with the theoretical predictions.

TABLE OF CONTENTS

I. INTRODUCTION

The overall objective of the CO laser program is the investigation of performance characteristics of a pulsed electrical CO laser using the electron beam sustained discharge excitation scheme. The primary goals of the initial program were:

1) The investigation of the electron beam current requirements and the E/p range for the discharge excitation of CO and $CO\text{-}N_2$ mixtures.

2) The design and construction of the electron gun and laser cavity for operation at gas temperatures from $100^{o}K$ to $300^{o}K$.

3) The extension of the theoretical model to the directly excited CO laser.

4) The experimental investigation of the multiline/multimode operation in cold CO mixtures.

Despite considerable delays in the fabrication of the variable temperature discharge electrodes, the above goals have been met with the main results being the successful construction and testing of a cryogenically cooled device with an output energy of up to 1 kilojoule. In addition, the following technical results were achieved during this initial program.

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II. ELECTRICAL SYSTEM AND COLD FLOW TESTS

Following the construction and testing of the individual electrical components, namely, the electron gun and the sustaining discharge capacitor supply, the entire electrical system was checked and room temperature lasing tests made using $He/N_2/CO_2$ gas mixtures at a half atmosphere pressure. For these measurements a simple stable resonator configuration using 10 cm diameter optics with 15% hole coupled output mirror was employed. . Several ground loop problems were observed and subsequently corrected during these tests. The system lased but no attempts were made to measure the output energy. An electron density in excess of $10^{12}/cm^3$ was deduced from the sustained discharge current measurements in good agreement with the predictions based on the estimated electron beam current density.[1]

Although these initial system tests were successful, a problem appeared in the erratic operation of the electron gun which developed internal arcing problems above 100 kV and also exhibited some cold emission. The arcing problem was traced to the failure of the nickel plating of the mechanical grid supporting the aluminum foil window. Apparently, the direct bombardment by the high energy electrons caused heating of the plated surface and subsequent failure of the plating adhesion to the surface. This resulted in flakes of nickel being distributed throughout the vacuum chamber with consequent increase in the local electric field near the jagged surfaces of the nickel flakes. After this problem was eliminated, it was found that cold emission

persisted as indicated by electron transmission through the foil despite the gun filaments being cold. The probable cause for this cold emission was traced to possible over-heating of one of the electron gun grid surfaces which was made of fine wire mesh. This problem was eliminated by redesign of the surface using a heavier grid material.

Separate tests were made to obtain an estimate of the uniformity of the flow and temperature field under cold operating conditions. These tests were made to obtain an estimate of the magnitude of transverse temperature gradients resulting from nonuniform gas flow in the cooled cavity operation (see Fig. 1). In these preliminary tests helium-neon probe laser beams were aligned along the laser axis as well as transverse as shown in Fig. 2. Since the cavity operates at constant pressure, any temperature gradient is reflected in a density gradient which will deflect the laser beam if the gradient has a component normal to the beam. It can be readily shown that the angular deflection of the beam, $\delta\Theta$, is given by[2]

$$\delta\Theta = (1-n) \frac{L}{\rho} \frac{d\rho}{dy}$$

where n is the refractive index in the gas, $d\rho/dy$ is the density gradient normal to the beam and L the overall path length. In CO as well as CO/N_2 mixtures, at the temperature of approximately $100^{\circ}K$, a normal temperature gradient of $1^{\circ}K/cm$ results in an angular beam deflection of approximately 300 μrads. In this simple experiment the limited spatial resolution resulted in a minimum detectable angular deviation

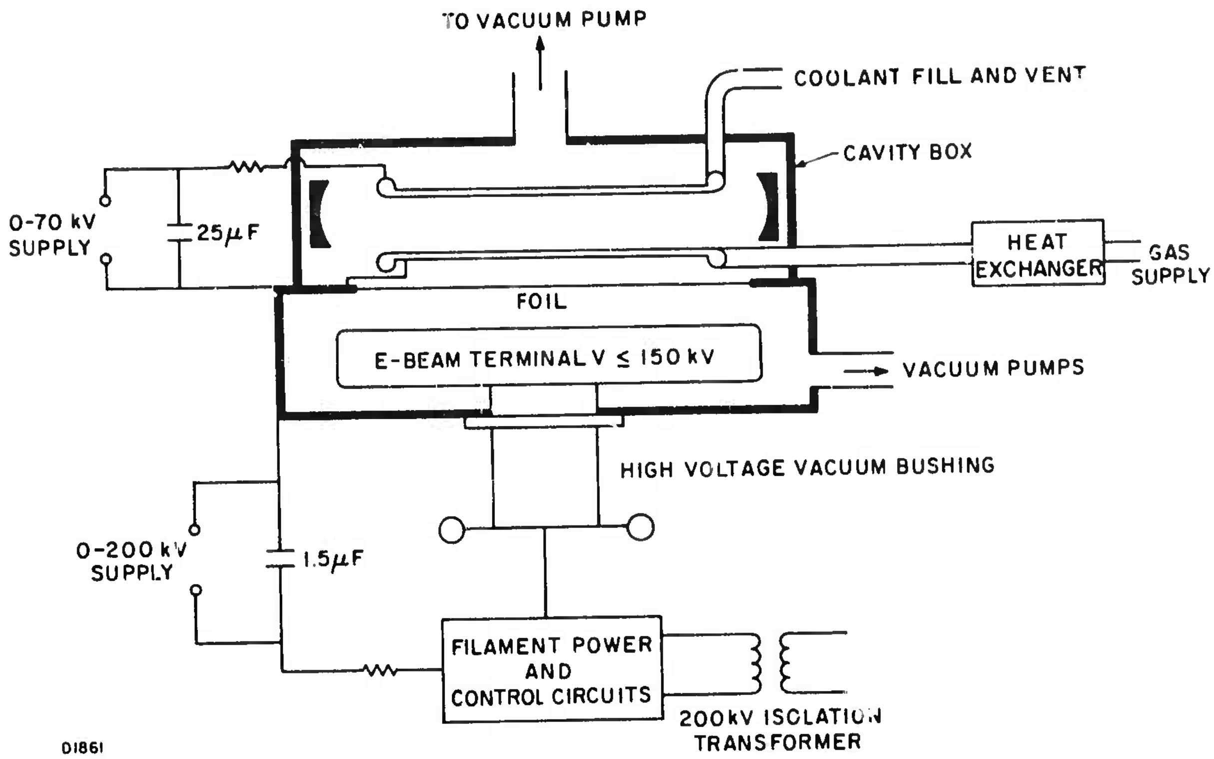

Fig. 1 Schematic of the 1 atm. CO Laser

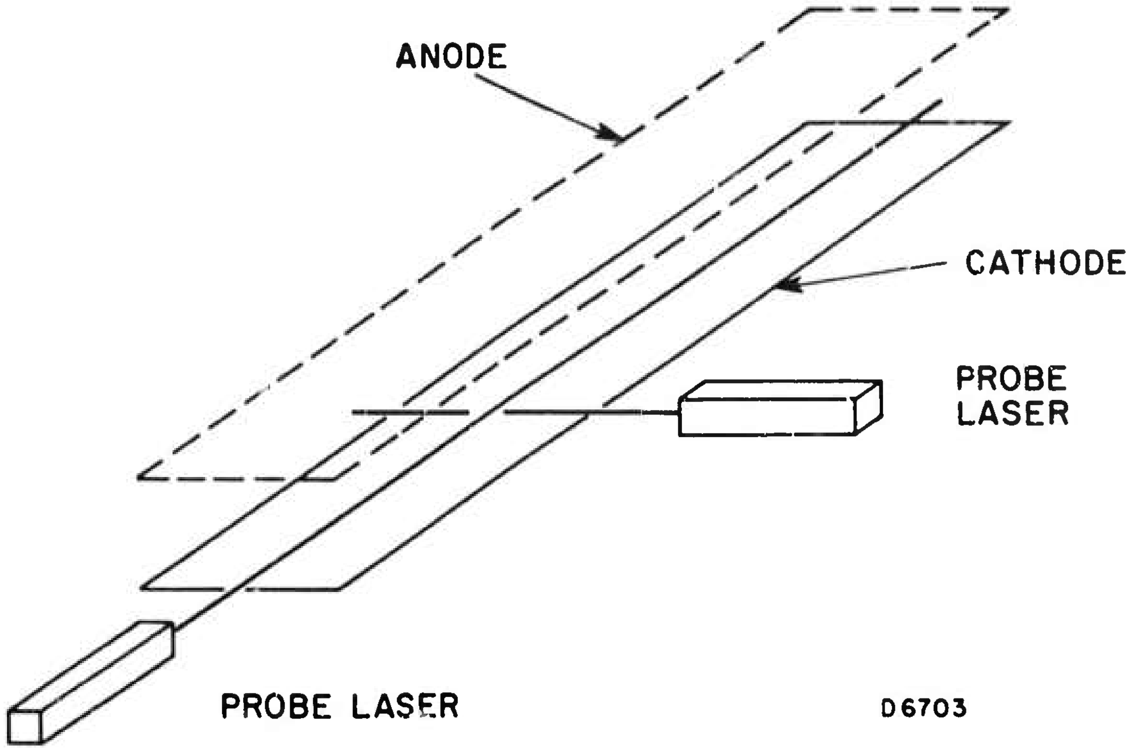

Fig. 2 Temperature Uniformity Test Set-Up

of approximately 400 μrads along the laser axis and somewhat less than this transverse to the laser axis. Measurements were made at several positions ranging from the center of the excitation volume towards either electrode as well as towards the edge of the excitation region. No angular deviation of the beams could be detected, and it was concluded that the maximum temperature gradients in the system must be of the order of or less than $1^{\circ}K/cm$. No net increase in the helium-neon probe beam diameter could be detected in these experiments. Somewhat more accurate and more detailed temperature variation measurements will be obtained in the future with the use of an optical interferometer.

III. BROAD AREA CALORIMETER

In the initial lasing tests a simple hole coupled stable resonator configuration was used necessitating the development of a broad area calorimeter to cover a significant diffraction of the cross sectional area, 10 cm x 20 cm. The basic requirements of such a calorimeter are:

1. High absorption at 5μ.
2. The surface should have a high melting point and high ablation temperature in order to prevent surface blow-off during the high peak power pulses.
3. The calorimeter should have high thermal conductivity to simplify the measurement of the overall temperature rise of the calorimeter.

Previous work in the CO_2 laser program had led to the development of flat anodized aluminum calorimeters[3] which proved to be very useful at 10μ. The surface absorption at this wavelength was shown to be in excess of 90% and thin oxide coating allows rapid energy transfer to the aluminum backing material. Unfortunately, such a simple system is not suitable in the 5μ region because the aluminum oxide coating has fairly high transmission at 5μ and this results in very small absorption of the incident energy.

A literature survey was made with the aim of finding metal oxides which might act as good absorbers in the 5μ region. This survey

indicated that the metal oxides of most common materials[4] were all reasonably good transmitters below 10μ. To overcome this problem it was decided to use a grooved anodized aluminum surface in which the grooves would permit multiple reflection of the incident beam[5] and thereby increased absorption before the beam escapes the surface. The absorption limit here is determined by the included angle in the grooved surface which for practical reasons was restricted to approximately 30°.

A 6 inch diameter anodized aluminum calorimeter was built with machined circular grooves, of 30° included angle, covering the entire surface. The temperature of this and a compensating surface was measured with several thermocouples mounted on the back of the surfaces as shown in Fig. 3. The unit was calibrated using low power cw laser beams at 10.6μ and in the 5-6μ region, the latter being provided by a multiline CO probe laser. Comparison of the results at these two wavelengths indicated an overall absorption of approximately 40-50% in the 5μ region. This was subsequently verified by the use of a totally reflecting hemispherical reflector mounted over the surface of the calorimeter.

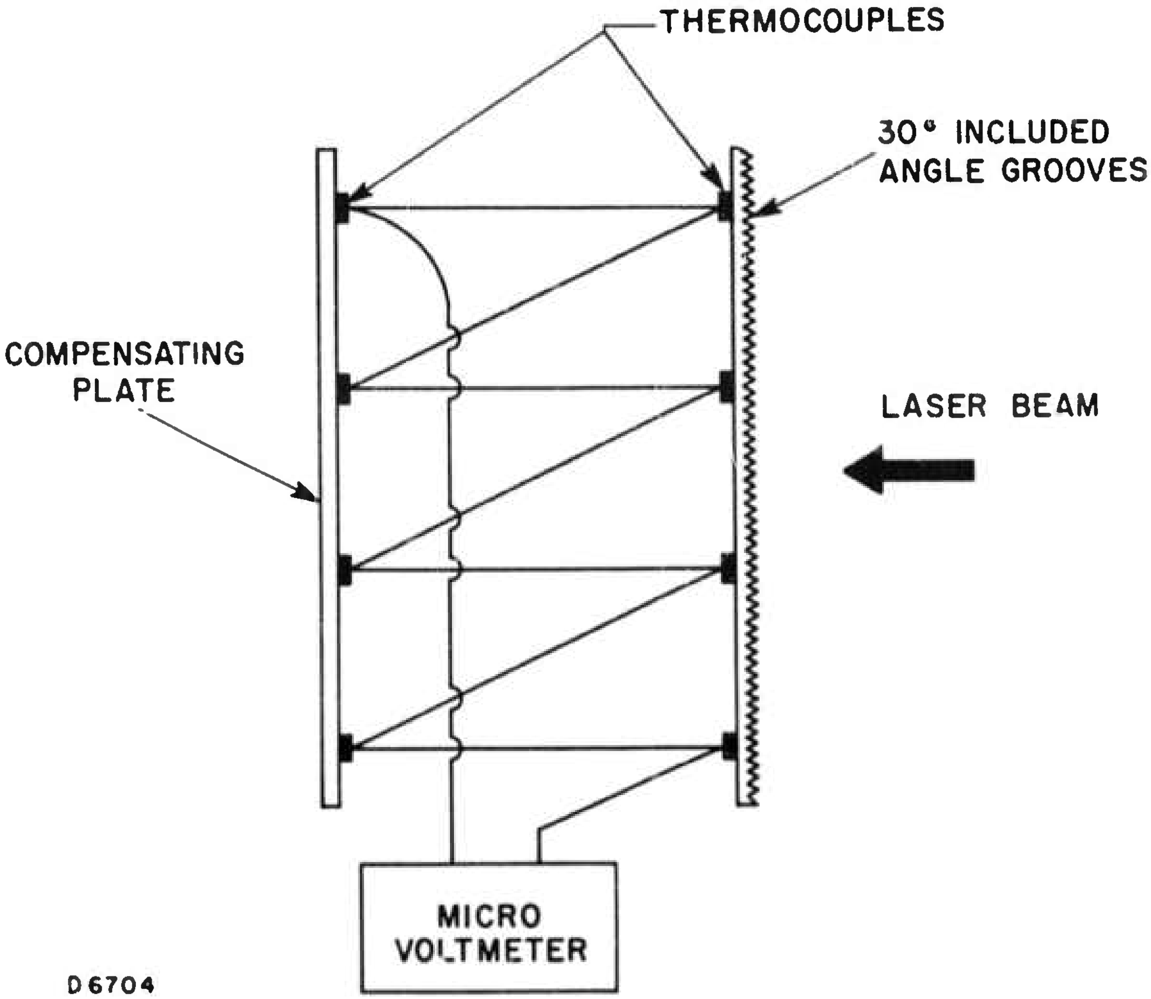

Fig. 3 Schematic of Anodized Aluminum Calorimeter

IV. COLD CO LASER TESTS

The basic data to be described in this section was obtained with a 33% hole coupled stable resonator containing the discharge, the pulse energy being monitored by the disk calorimeter described in the previous section. All the measurements were made under cold conditions with the discharge electrodes precooled to 80°K, and the initial gas temperature being approximately 100°K at the entrance to the cathode electrode. Some early measurements made in both pure CO as well as 50% CO 50% N_2 mixtures indicated far greater output energy for the CO/N_2 mixture which was used in all subsequent tests. A NaCl output window was used and the calorimeter mounted so as to monitor half the output beam. Several tests were made to verify the symmetry of the output beam.

The measurements included the total pulse energy, the temporal variation in the sustaining discharge voltage and current as well as the variation in the laser pulse shape. Nominal test conditions were temperature 100°K, electric field 2.5 kvolts/cm, pressure 1/6 of atmosphere and electron beam voltage 140 kv. Typical discharge voltage and current characteristics are shown in Fig. 4. The droop in the sustaining voltage and current profiles is a result of the limited storage in the sustaining discharge capacitor bank. Although the capacitor bank has a possible storage capacity of 45 kilojoules, it was restricted to approximately 11 kilojoules by the wiring configurations used for these 25 kv tests and the finite energy drawn from the bank

$T \lesssim 100^\circ K$

$P \simeq 1/6$ ATM

$\rho \simeq 1/2$ AMAGAT

$\psi_{CO} = 1/2$

$\psi_{N_2} = 1/2$

$V_S = 25$ kV

$V_{EB} = 140$ kV

COUPLING 33 %

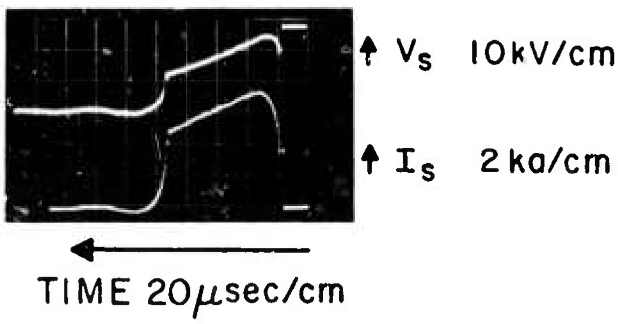

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Fig. 4 Typical Sustaining Discharge Current and Voltage Profiles

resulted in a significant voltage drop at the output. This condition can and will be remedied in the future by rewiring of the sustainer capacitor bank.

The variation in pulse energy as a function of pulse length is shown in Fig. 5 for pulse lengths in the range of approximately 20-90 microseconds. The maximum pulse energy is of the order of 1 kilojoule with an overall total electrical efficiency of approximately 15%. The error bar shown in the figure reflects the uncertainty in the calorimeter calibration as well as the pulse-to-pulse variation in the output energy. The finite delay time before the threshold gain condition is reached, as shown in Fig. 5, is a direct result of the finite kinetics involved in the redistribution of vibrational energy in the CO molecule. The small increase in the output energy for pulse lengths greater than 40 microseconds reflects the effect of the falling sustainer voltage and sustainer current.

These results can be compared with the predictions based on the AERL CO laser kinetic model for the electrically excited CO/N_2 laser. Basically, this model numerically integrates the vibrational relaxation equation describing the population density of each vibrational level in the CO molecule including collisional terms, electron impact excitation terms, and of course the stimulated emission terms. The model assumes a steady state oscillation condition in which gain equals loss on all oscillating transitions. Results predicted by this model for the present experiment are shown in Fig. 6 which gives the temporal variation in the efficiency as well as the translational temperature rise.

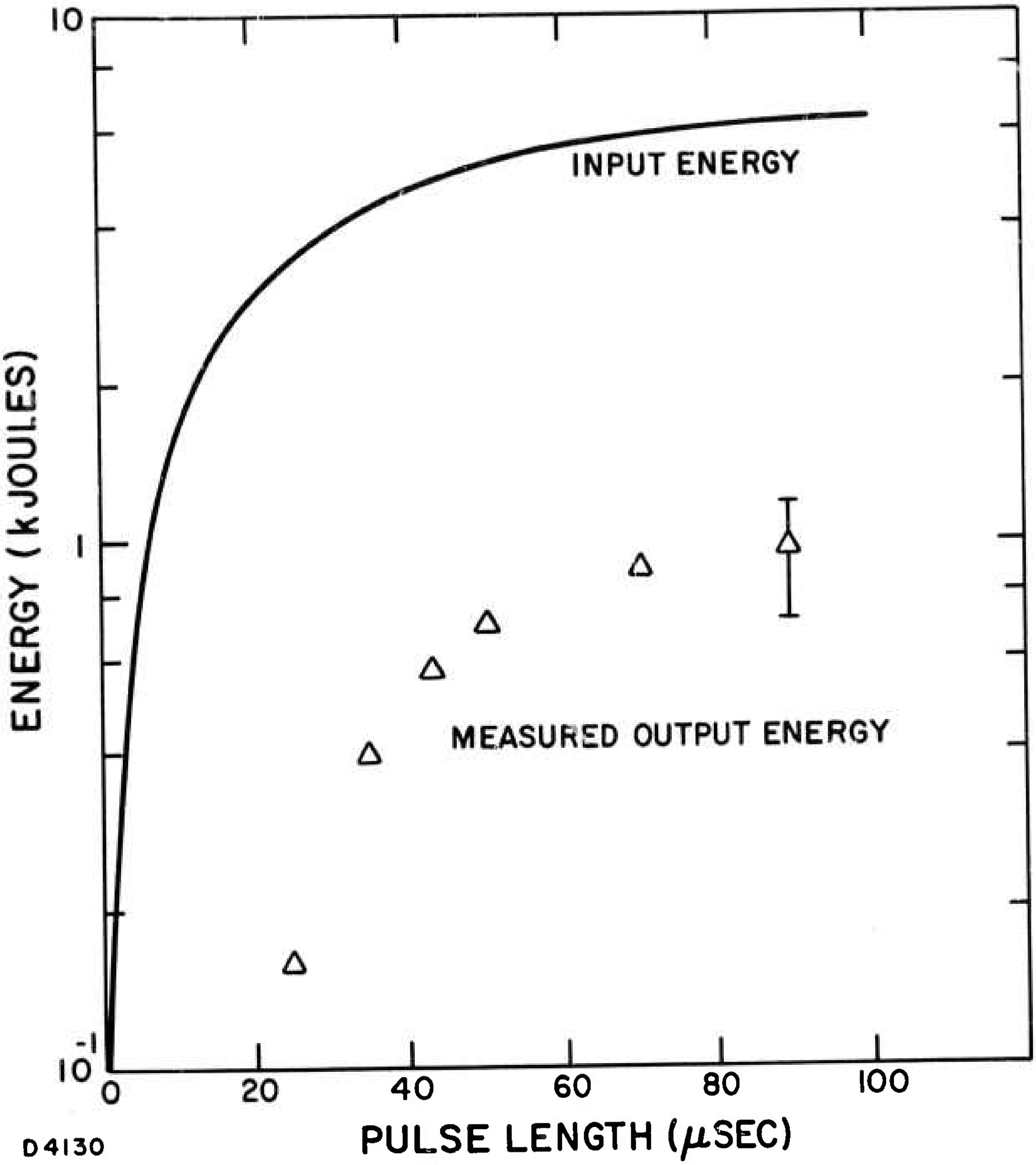

Fig. 5 Variation of Pulse Energy with Pulse Length under Nominal Operating Conditions Shown in Fig. 4

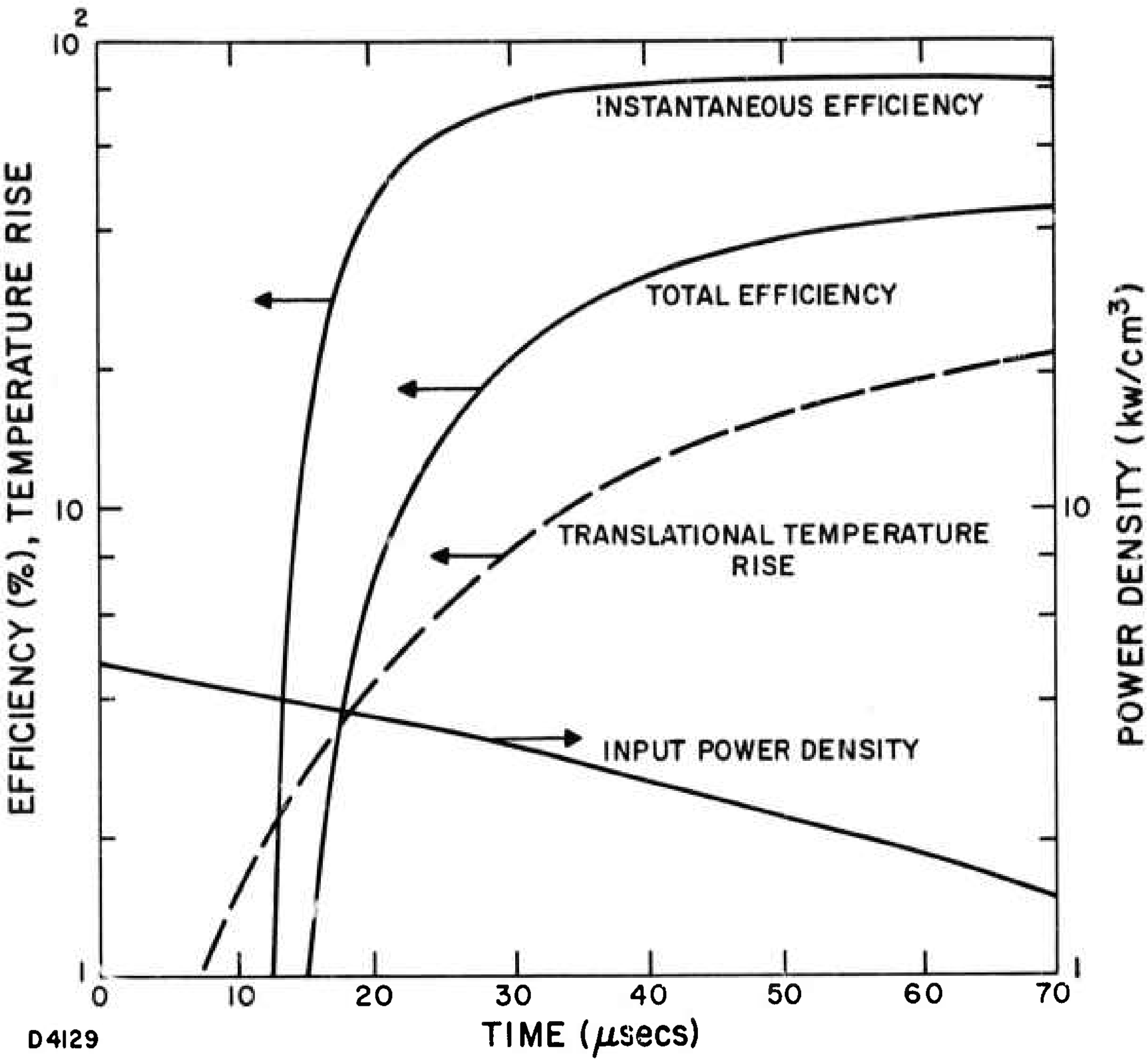

Fig. 6 Theoretical Predictions for Laser Performance using AERL Kinetic Model. Input conditions correspond to nominal operating conditions shown in Fig. 4.

Two efficiency curves are shown, one the instantaneous local efficiency and the second the total of efficiency defined as the integrated output energy over the net input electrical energy. Also shown in the figure is the input power density profile used to simulate the sustainer discharge pulse. The finite rise time or switch on time for the discharge pulse has been neglected in this calculation. By comparisons with Figs. 5 and 6 it is evident that the experimental result for the total efficiency is a factor of 2-3 lower than predicted by the numerical model.

There are several possible reasons for the discrepancy between the theoretical and experimental result of the overall lasing efficiency. The first of these is related to the measurement of the current uniformity and current density in the sustaining discharge. For these experiments the total discharge current was measured and the current density derived from the assumed cross section of the electron beam. However, the discharge electrodes are considerably larger than the nominal beam area and because of scattering of the electron beam the discharge is known to be considerably larger. This results in an overestimate of the electron density in the optical cavity. Some preliminary measurements using isolated small area current buttons, mounted in the anode, indicated some nonuniformity in the discharge current density with a significant fall off towards the edge of the anode. Another major uncertainty is the actual gas temperature within the excitation region as well as temperature fluctuations. Although the gas temperature at the entrance to the cathode was measured to be approximately 100°K, the temperature within the excitation region may be higher as a result of the proximity

of warm wall surfaces to the discharge. In particular the warm foil window located directly underneath the cathode (see Fig. 1) probably leads to boyant plumes rising through the porous cathode structure, and it is certainly possible that the temperature in the excitation region may be considerably higher than the measured inlet temperature. Furthermore, the increase in the translational temperature may be somewhat larger than predicted. A calculated temperature rise shown in Fig. 6 reflects only the energy transferred to the rotation-translational degrees of freedom as a result of deactivation collisions as well as the energy defect or access in vibrational exchange collisions. The predicted rise in the translational temperature as a result of the direct excitation of the rotational degree of freedom by electron impact[6] is small in comparison with the temperature increase due to the collisional kinetics. However, the cross sections for rotational excitation are not well know and it is certainly possible that the temperature rise is larger than predicted. All these problems and uncertainties will be examined in the continuation of this program.

A liquid nitrogen cooled GeAu detector was used to monitor the temporal variation in the lasing pulse shape by matching the energy scattered from the diffuse reflector. Theoretical and experimental profiles are compared in Fig. 7 in which the peak output flux has been normalized to unity. Although the overall pulse shapes are quite similar, the energy content of the experimental pulse is smaller than predicted and the predicted delay time before reaching threshold gain condition is some 5 microseconds shorter than the experimental result.

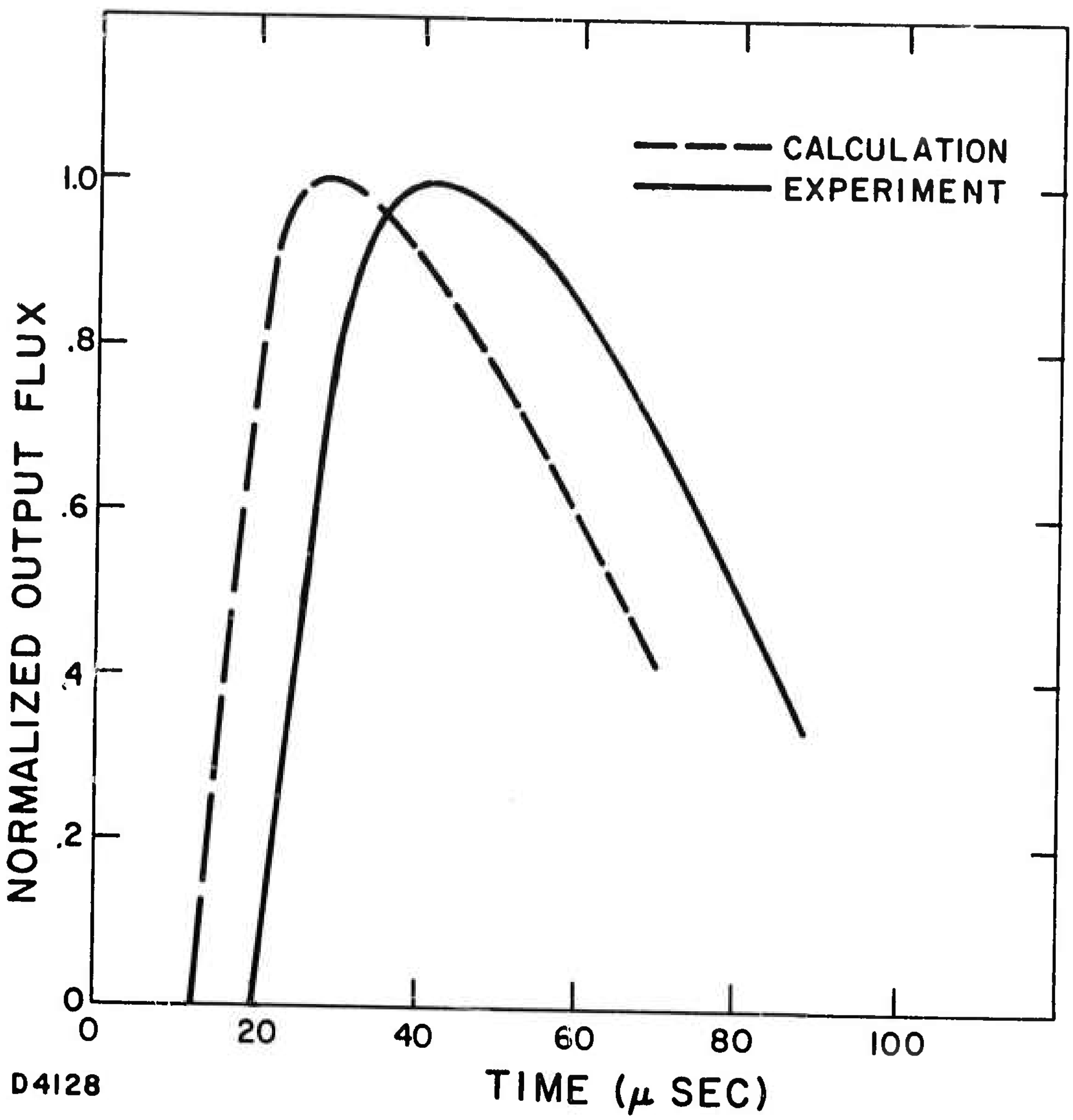

Fig. 7 Comparison of Theoretical and Experimental Pulse Profiles which have been Normalized to Unity at Peak Intensity

This is due in part to the neglect in the theoretical calculations of the finite rise time in the discharge current profile. This finite rise time is illustrated in Fig. 5. This delay time is a direct result of the finite kinetic rates for the vibrational relaxation processes and is dependent upon these rates. Because of the lack of low temperature measurements on the vibrational exchange rates, they have been calculated theoretically for use in the present modeling calculations. It is anticipated that more detailed experimental measurements of the temperature variation of these kinetic rates will be available in the near future.

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